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THE DESIGN AND OPERATION OF THREE POWER SUPPLIES FOR THE IMP-I SPACECRAFT

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GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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FOREWORD

The purpose of this document is to describe the design and operation of three different power supplies for the IMP-I spacecraft. These are the Encoder Converter (IP-7), the Decoder Converter (IP-5), and the Plasma Experiment low voltage power supply (a subsystem of GOP). The reasoning behind the design approach chosen to meet the specifications peculiar to each unit as well as those common to all three units are discussed, and the performance of each unit under all anticipated conditions of operation is presented.

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ILLUSTRATIONS

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ILLUSTRATIONS (continued)

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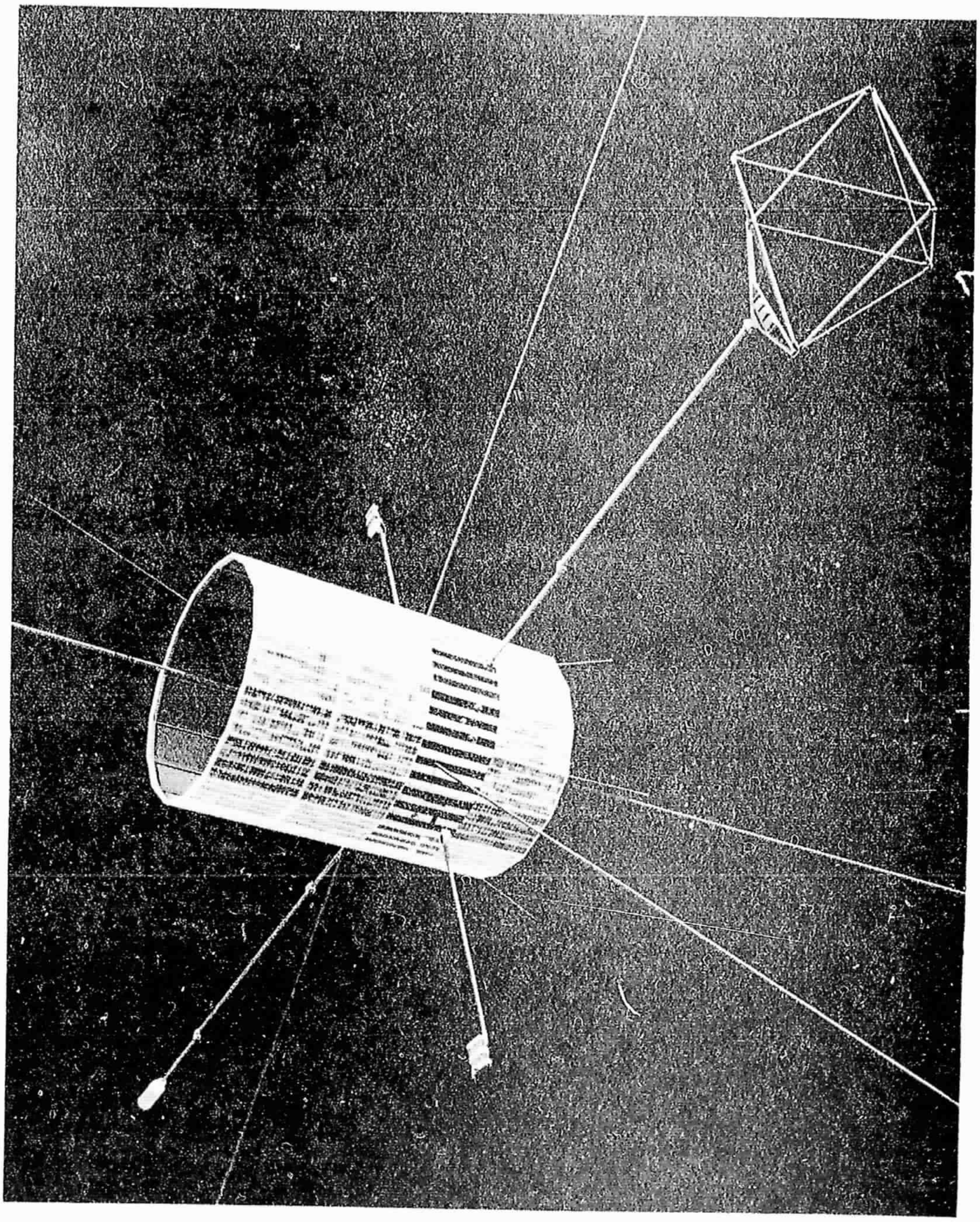


Frontispiece — IMP-I Spacecraft, Artist's Conception

THE DESIGN AND OPERATION OF THREE POWER SUPPLIES FOR THE IMP-I SPACECRAFT

INTRODUCTION

The basic techniques of DC to DC voltage conversion by purely electronic means have long been known and used. Spacecraft power systems present many opportunities to employ this type of power conditioning due to the nature of space power sources and the varied requirements of the loads. Certain basic aspects of design are common to all DC to DC converters, while other aspects are unique to a particular unit in fulfilling the design specifications supplied by the user. In the discussion to follow the specifications are first presented. From a consideration of the specifications there evolves a general design approach for all three power supplies. This is followed by a presentation of details peculiar to each unit. Those areas involving standard and commonly used techniques of design will be glossed over quickly, while areas considered of greater interest will be gone into in more detail.

It will be noticed in the reading that although all three units perform essentially the same function, i.e., supply multiple DC output voltages from a single DC input voltage, the details of their design are in fact quite different.

DESIGN SPECIFICATIONS

Below are tabulated the specifications each unit must be designed to meet.

Decoder Converter

This power supply is to consist of two separate and independent units with one output from each, as indicated below, OR gated for redundancy.

Input Voltage: +28 volts DC ±2%

Output Voltages and Loads:

	Output Volts			Output Current (ma) Minimum	Output Current (ma) Maximum
No. 1	+12.7 volts		±1%	32	105
	+12 volts				
		OR gated	±3%	76	112
No. 2	+12 volts				
	+12.7 volts		±1%	92	137
	-12 volts		±1%	15	25
	+5 volts		±1%	161	236

Temperature Range: -20°C to +50°C

Frame and Connectors: One complete IMP-I card, with two connectors, one Cannon 25 pin male and one Cannon 50 pin male. The approximate dimensions are as shown in Figure 1.

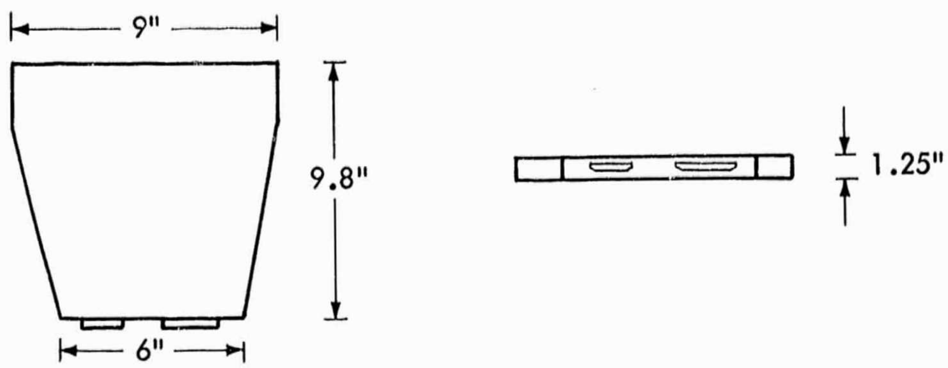


Figure 1. Decoder Converter Frame Dimensions

The following items were not originally specified. The figures given are those set by the designer as being reasonable.

Output Voltage Ripples: 30 mv or less peak to peak on all lines.

Input Current Ripple: 5 ma or less peak to peak.

Input Ripple Voltage: 30 mv or less peak to peak.

Efficiency: 70% or more at maximum load.

Encoder Converter

Input Voltage: +28 volts DC ±2%

Output Voltages and Loads:

Output Volts		Output Current (ma) Minimum	Maximum
+12 volts	±5%	4	25
-10 volts	±5%	3	20
+7.75 volts	±1%	250	780
-2 volts	±5%	200	750

Temperature Range: -20°C to +50°C

Efficiency: 70% at maximum load and 60% at minimum load.

Frame and Connectors: One partial IMP-I card, with one 100 pin male Deutch connector. The approximate dimensions are as shown in Figure 2.

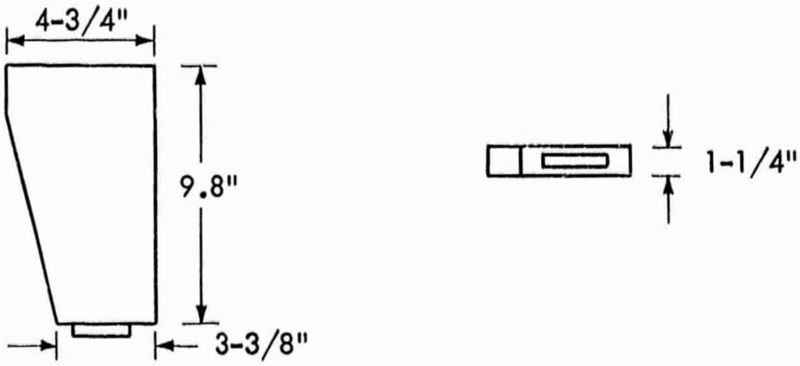


Figure 2. Encoder Converter Frame Dimensions

The following items were not orginally specified. The figures given are those set by the designer as being reasonable.

Output Voltage Ripples: 30 mv or less peak to peak on all lines

Input Current Ripple: 5 ma or less peak to peak

Input Ripple Voltage: 30 mv or less peak to peak

Plasma Experiment Power Supply:

Input Voltage: +28 volts ±2%

Output Voltages and Loads:

Output Volts	Output Current (ma)	
	Minimum	Maximum
+12 volts 2%	20	20
+11.7 volts 2%	95	190
+5 volts 3%	260	260
+3.5 volts 4%	400	800
-3.5 volts 4%	100	100

Temperature Range: $-10°C$ to $+40°C$

Output Ripples: 1.0% of nominal output voltage peak to peak

Efficiency: Maximum possible within the present state of the art.

Short Circuit Protection: The power supply shall turn off if any or all of the outputs are shorted. The unit shall restart upon removal of the short(s).

Frame and Connectors: One partial IMP-I frame with one 37 pin male Cannon connector. The approximate dimensions are as shown in Figure 3.

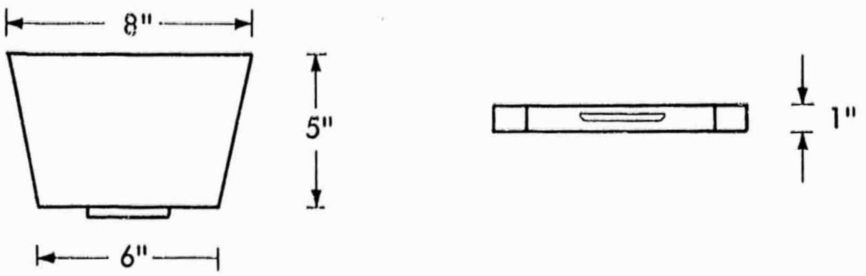


Figure 3. Plasma Experiment Power Supply Frame Dimensions

The following items were not orginally specified. The figures given are those set by the designer as being reasonable.

Input Current Ripple: 5 ma or less peak to peak

Input Voltage Ripple. 30 mv or less peak to peak

In addition to the above specific requirements, all subsystems in the IMP-I spacecraft had to conform to the following:

1. All power oscillators to operate at 20 KHz ±3%
2. All inputs to be DC isolated from the outputs and all inputs and outputs to be DC isolated from the frame.
3. All subsystems must successfully undergo the environmental specifications outlined in 'Environmental Test Specifications for the Interplanetary Monitoring Platform IMP-I Subsystems,' S-320-IMP-4. This includes thermal vacuum soak, vibration, magnetic and RFI tests.

GENERAL DESIGN APPROACH

There are two basic types of building blocks used in the design of DC to DC power supplies. These are the oscillator, or chopper, which converts the DC to AC and then back to various levels of DC; and the DC voltage regulator. All three units require these in varying quantities and arrangements to best suit the needs. As usual, the basic ideas to keep in mind are minimum parts and efficiency. In this regard it is best to avoid a situation where there are essentially two regulators in series, i.e. on the input and output sides of a converter. It is also desirable to avoid regulating the lower voltages such as the -2 volts and +3.5 volts since this is difficult to do efficiently.

Since all oscillators must operate at 20 KHz ±3%, an initial study was performed on a typical multiple output converter to determine if it could maintain this requirement over variations in input voltage, temperature and load without special techniques being employed. This study showed it could be done, but each oscillator would require careful triming to achieve this. If a regulator should preceed the oscillator, the problem is greatly eased.

Decoder Converter: This unit will require two separate and independent oscillators due to the +12 volt redundancy required. Also, since each output except the +12 volts is required to be within 1% over the temperature, load and input voltage range, an output regulator for each voltage is required. The block diagram for this power supply is shown in Figure 4.

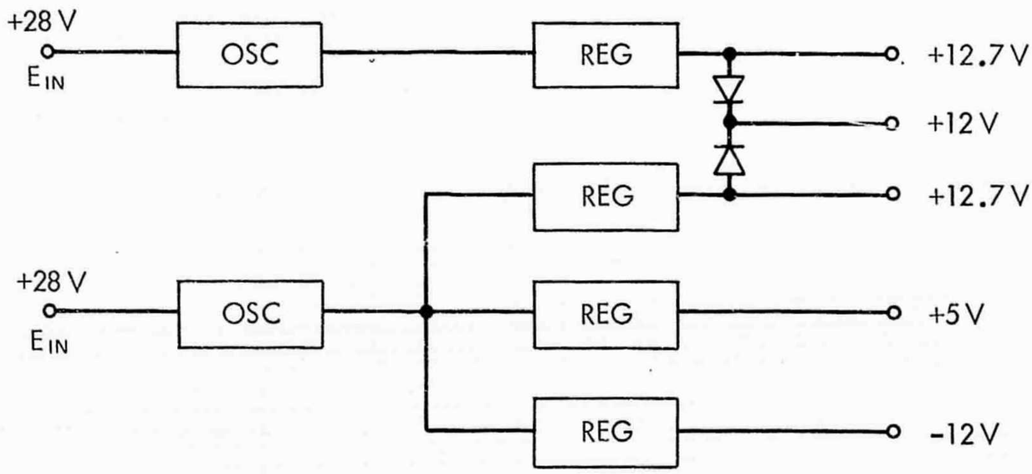


Figure 4. Block Diagram for the Decoder Converter

Encoder Converter: This unit will require one oscillator, and has only one stringent output requirement in the 1% regulation on the +7.75 volt output. Therefore, this output will have to be regulated. The -2 volt output, although allowed

a 5% leeway, is also a fairly tight tolerance since it must remain within a 200 millivolt range. It was decided not to try and regulate this output, but special techniques had to be employed in order to meet the specification. The block diagram for this unit is shown in Figure 5.

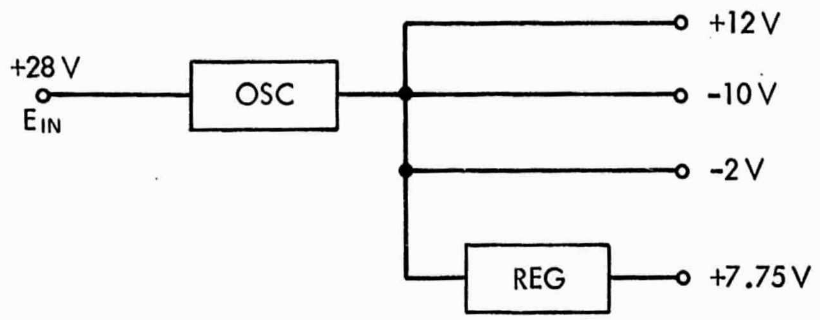


Figure 5. Block Diagram for the Encoder Converter

Plasma Experiment Power Supply: This unit has a fairly broad tolerance on all its outputs, but some regulation will be required. Therefore it was decided to use a single input regulator followed by the oscillator. As will be noticed in the performance data, this arrangement greatly facilitates staying within the 20 KHz ±3% frequency requirement placed on all the oscillators. The block diagram for this unit is shown in Figure 6.

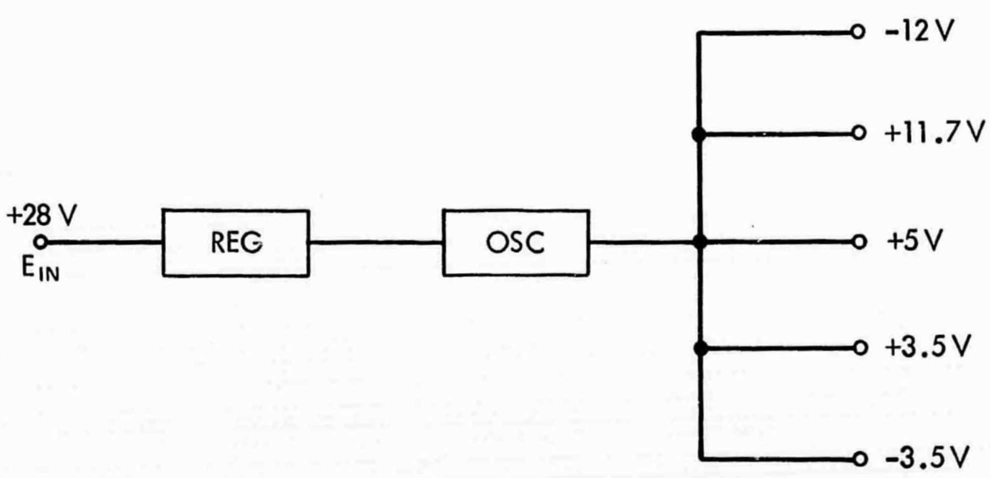


Figure 6. Block Diagram for the Plasma Experiment Converter

OSCILLATOR

All three power supplies incorporate the two core magnetic oscillator commonly known as the Jensen square wave oscillator. This circuit has seen considerable use in the power conversion section at GSFC, and is shown in Figure 7.

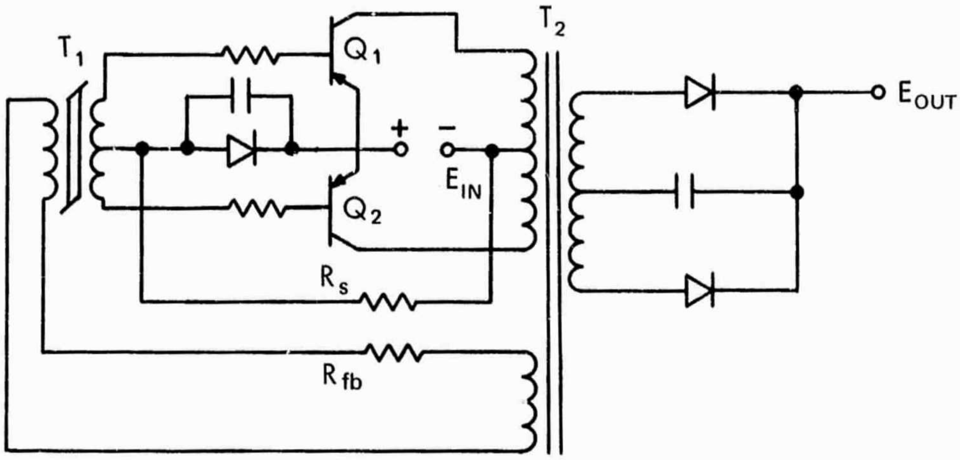
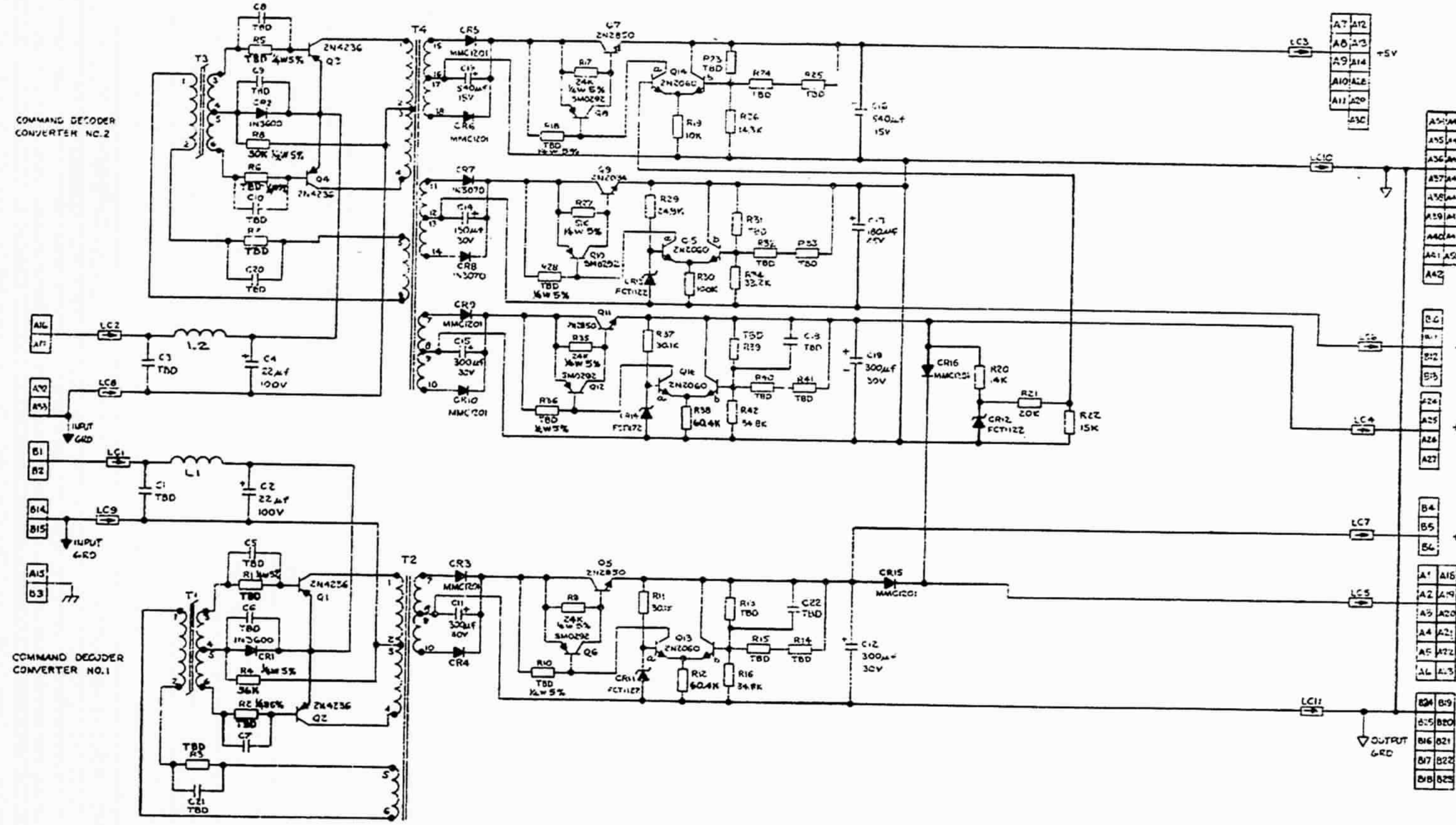


Figure 7. Two Core Magnetic Oscillator

Briefly, the circuit works as follows. Sufficient current is supplied through R_s to turn on either Q1 or Q2. Once either of these two transistors turns slightly on, a small voltage appears across the primary of T2. Since the oscillator is designed to have a loop gain greater than one, regeneration rapidly turns the transistor on hard. The on transistor remains saturated until transformer T1 saturates. At this time current in the feedback loop rapidly rises to a vlaue determined by R_{fb} and the feedback drive to the on transistor is rapidly reduced below that necessary to supply the existing load and sustain the operating condition. At the end of the on transistor's storage time it begins to turn off rapidly, causing the feedback current through R_{fb} to also fall rapidly. This condition causes a voltage reversal in all T1 windings due to the energy stored in its primary winding. Thus the next half cycle is initiated. In actuality, the secondary winding supplying E_{out} is several separate windings since most supplies require multiple outputs. T2 is typically designed to make use of anywhere from 50% to 80% of its flux capacity.

REGULATOR DESIGN

In the three power supply designs there are a total of six voltage regulators. These are all of the same basic design with variations to suit particular needs.



NOTE:
1. HIGH NO'S C22 L2 CR16 T4 R42 LC11 Q16
2. CASE GROUND
3. PIN CONNECTION DESIGNATION
A: 50 PIN CANNON
B: 26 PIN CANNON
4. ALL RESISTORS 1/8W 1% UNLESS OTHERWISE SPECIFIED
5. Q1—Q5, Q11, Q9 AND Q7 HEATSINKED

BENCH TEST THERMISTORS

Figure 8. Decoder Converter Schematic

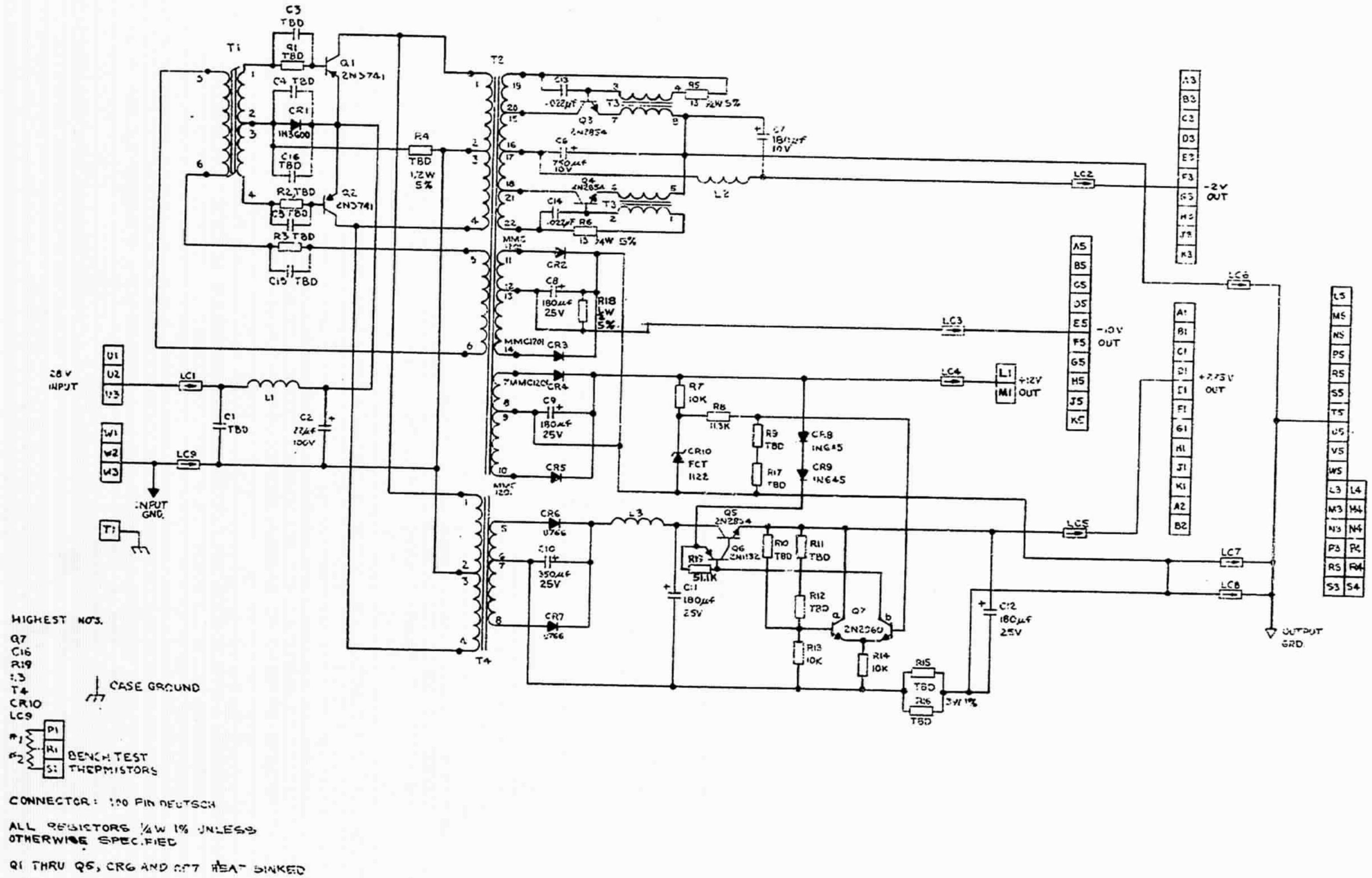


Figure 9. Encoder Converter Schematic

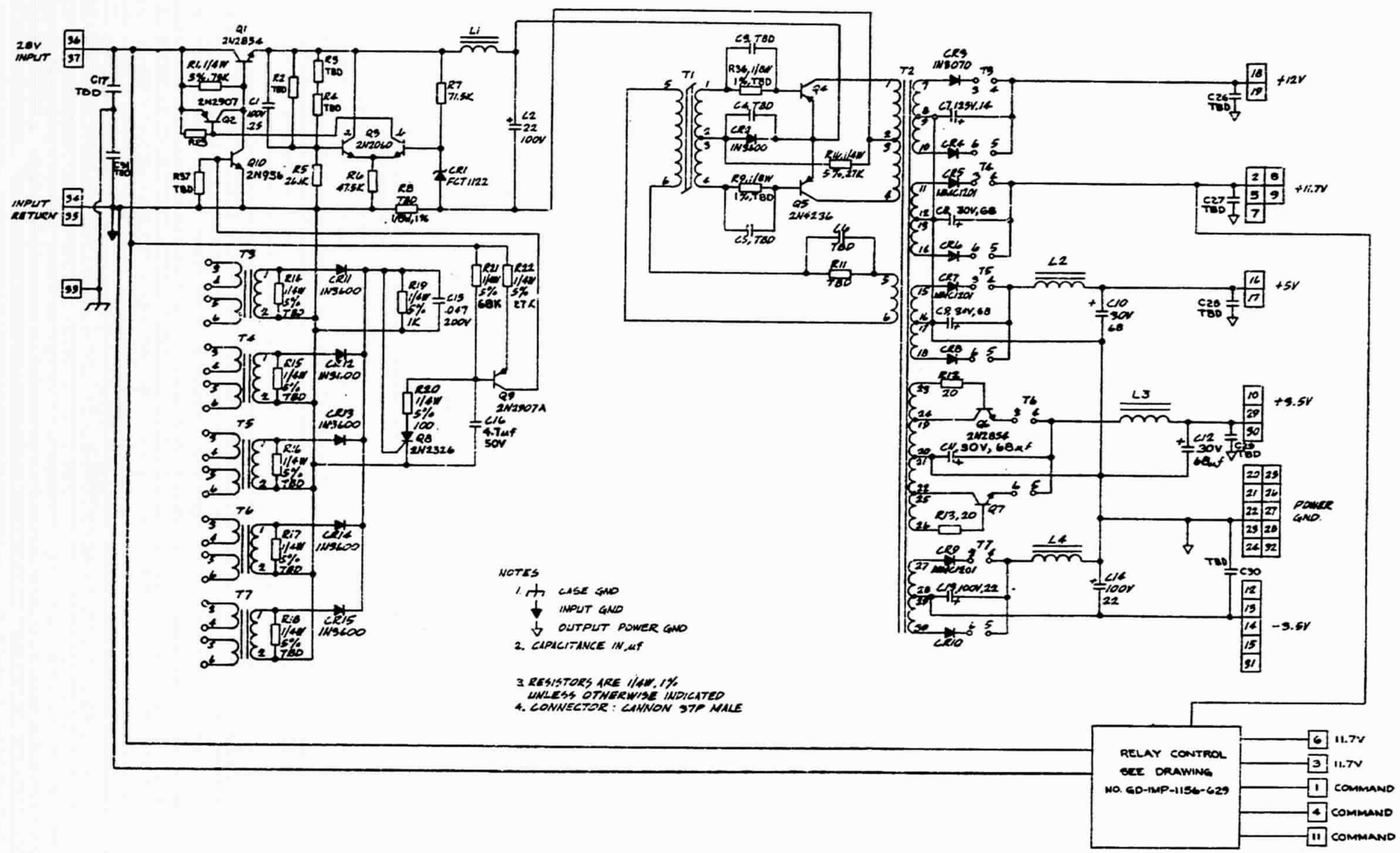


Figure 10. Plasma Experiment Converter Schematic

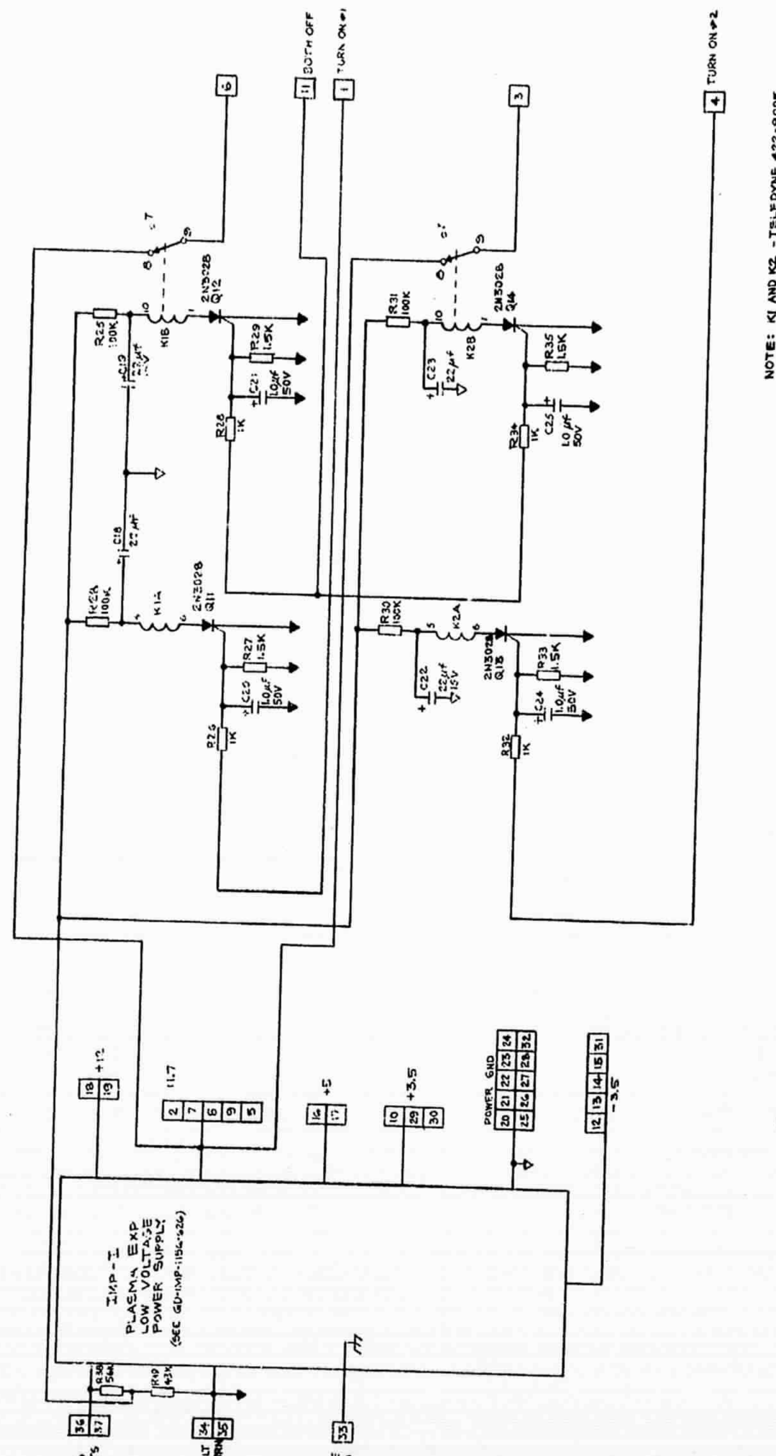
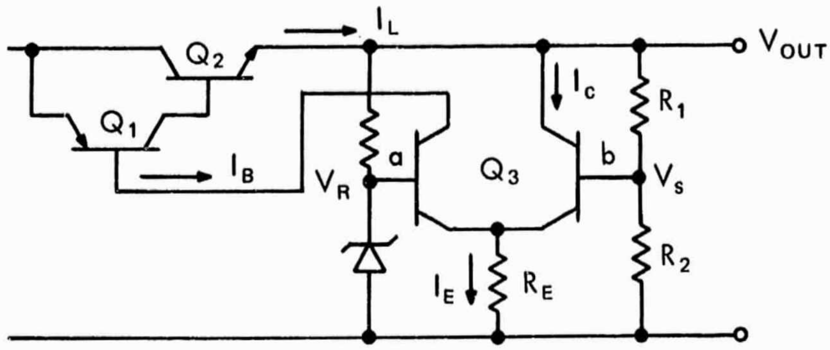


Figure 11. Plasma Experiment Load Switching Schematic

The basic design chosen uses the voltage to current feedback technique whereby voltage variations in the output cause a corresponding change in drive current to the series pass element. This is shown in Figure 12.



V_r = REFERENCE VOLTAGE

V_s = SAMPLE VOLTAGE

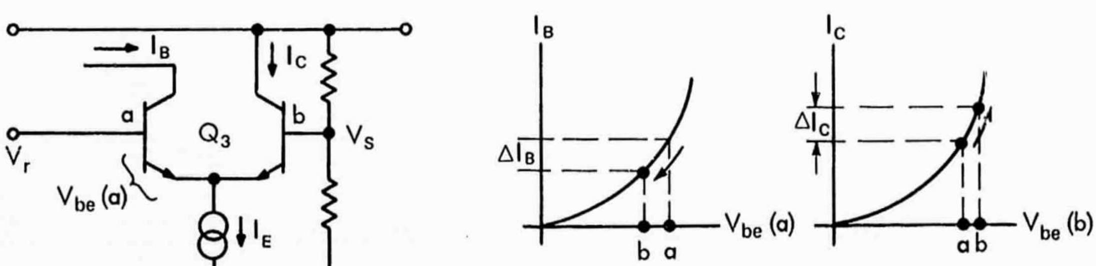
$I_c + I_B = I_E$

$\Delta I_b = f(\Delta V_{out})$

$I_L = \beta_1 \beta_2 I_b$

Figure 12. Basic Regulator Configuration

All the regulators use the FCT 1122 zener diode either directly or divided down. This device is nominally rated at 7 volts, is very stable and may be used with as little as 100 microamps through it. Figure 13 helps to explain the action of the differential amplifier as used in these regulators.



$\Delta I_B = -\Delta I_C$

VERTICAL AXIS: β_{Q3} X Q_3 BASE CURRENT

Figure 13. Differential Amplifier and Base Emitter Diode Characteristics

Since the current through R_e in Figure 12 remains essentially constant, it may be represented as a constant current source as depicted in Figure 13 (a). Any changes in V_{out} shows up as a change in V_s. This in turn causes a change in the base emitter voltages of Q3 (a) and (b). Figure 13 (b) shows typical base

emitter diode characteristics. A slight increase in V_{out} has caused an increase in I_c and a decrease in I_b. The total change in the base emitter voltage of both transistors will always be equal to the change in the sample voltage, i.e.,

$$\left| \Delta V_{be}(a) \right| + \left| \Delta V_{be}(b) \right| = \Delta V_s = \frac{R_1}{R_1 + R_2} V_{out}$$

The relationship between the change in collector current and the change in output voltage is as follows:

$$I_c = e^{V_{be}/h}$$

$$\Delta I_c = I_{se}{}^{V_{be}/h} \left(e^{\Delta V_{be}/h} - 1 \right)$$

$$\Delta I_c = K \left(e^{\frac{R_1}{R_1 + R_2} \frac{\Delta V_{out}}{2h}} - 1 \right)$$

where

$$I_s = \beta_{Q3} \text{ X reverse saturation current}$$

$$h = \text{diode curve const.}$$

In this example, I_c and I_b are shown as initially equal on the curves of Figure 13 (b). It may be shown that while the gain, or transconductance in this case, of the differential amplifier is proportional to the magnitude of the total emitter current I_e, it is independent of the relative magnitudes of I_c and I_b.

The +7.75 volt regulator in the Encoder Converter and the input regulator in the Plasma Experiment power supply have a modification whereby the load current is sensed and adjusts the reference voltage. This is shown in Figure 14.

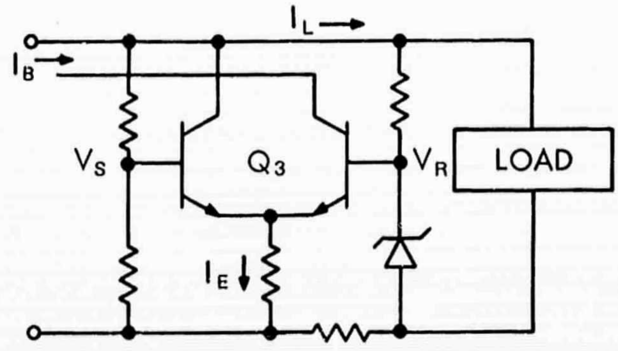


Figure 14. Basic Regulator Design with Feedback Resistor Added

The reference voltage increases with increasing load current, thereby increasing the base drive to the series pass element. This offsets the tendency of the output voltage to drop with increasing load. R_{fb} can be adjusted to give any output impedance desired over a fairly large output current range. The value of R_{fb} used in both regulators is about 0.1 ohms. From the curve of Figure 26 showing the 7.75 volt output voltage as a function of load, it is seen that very low output impedances may be realized without going to extremely high gain devices in the regulator. The output impedance of the 7.75 volt regulator over the load range of 200 to 700 ma is seen to be essentially zero.

One other refinement used on the 7.75 volt regulator in the Encoder Converter is the use of a separate voltage source for Q6 (Figure 9). Since the load current could become approximately 800 ma, it is beneficial to keep the voltage across Q5 (Figure 9) to a minimum. In the normal compound connection, the series pass element and its driver must operate nominally at about 1.5 volts, since it needs a minimum of 1 volt for proper operation, as shown in Figure 15 (a).

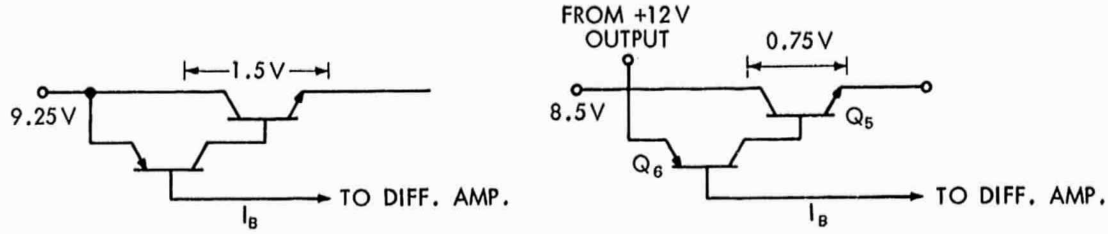


Figure 15. Series Pass Connection Variations

In Figure 15 (b) is shown the situation as exists in the Encoder Converter. Q5 can be operated effectively to saturation and nominally has about 0.75 volts across it. This represents a savings of approximately 0.6 watts, which helps both the efficiency and reliability.

SYNCHRONOUS RECTIFIERS

Often, when supplying low voltages from a DC to DC converter, it is advantageous to use synchronous recitifiers rather than diode rectifiers. This is particularly true when higher current levels, such as several hundred milliamps or more, are involved. Both the Encoder Converter and the Plasma Experiment power supply use this type of configuration. Figure 9 shows the synchronous rectifier used in the Encoder Converter. It is made up of Q3, Q4, C6, C7, C13, C14, R5, R6, L2 and T3. This design utilizes proportional current drive by means of current transformer T3. In this configuration the base drive voltage is actually applied between the base and collector, making a common collector circuit. This is true of all synchronous rectifier circuits since otherwise the transistors would not be able to withstand the reverse voltage during their off time.

Capacitor C13 and C14 turn each transistor on hard at the start of their conducting half cycle since the magnetizing current through T3 is not sufficient to do this. These capacitors also help facilitate fast turnoff.

The primary advantage in using the synchronous rectifier over a switching diode rectifier is the lower output impedance realized for the -2 volt and +3.5 volt outputs. Figure 16 gives the typical characteristics for a 2N2854 NPN high speed silicon transistor and a U-766 silicone switching diode.

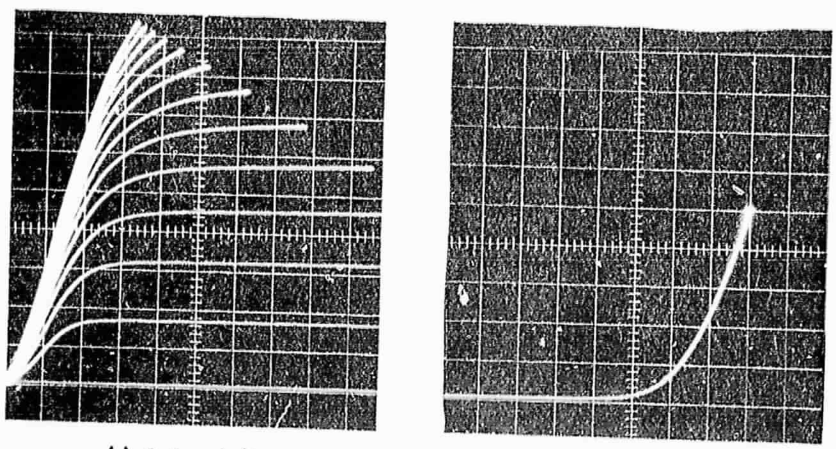


Figure 16. Rectifier Transistor and Diode Characteristics

Figure 16 (a) shows the saturation resistance for the 2N2854 to be approximately 0.15 ohms over the current range of 0 to 800 milliamps. On the cther hand, Figure 16 (b) shows the diode dynamic resistance to vary considerable over this same range. The equivalent resistance a load variation of 200 to 800 milliamps would see using the diode is approximately 0.23 ohms. The proportional current drive used in the Encoder Converter synchronous rectifier further reduces the effective resistance of the saturated 2N2854 to approximately 0.1 ohms, as may be verified by careful examination of Figure 16 (a).

The synchronous rectifier used in the Plasma Experiment power supply is essentially the same except it does not use proportional current drive. The load change is less and the tolerance greater on this output so the simpler configuration was used. Figure 10 shows the synchronous rectifier, which is made up of R12, R13, C11, C12, Q6, Q7, and L3.

Figure 17 shows the collector current waveforms of both synchronous rectifiers at maximum and minimum loads. The Encoder Converter shows fairly constant, fast and low level reverse recovery current as compared to the Plasma Experiment power supply, even though the load change in the Encoder Converter output is greater. This is another advantage of the proportional current drive technique.

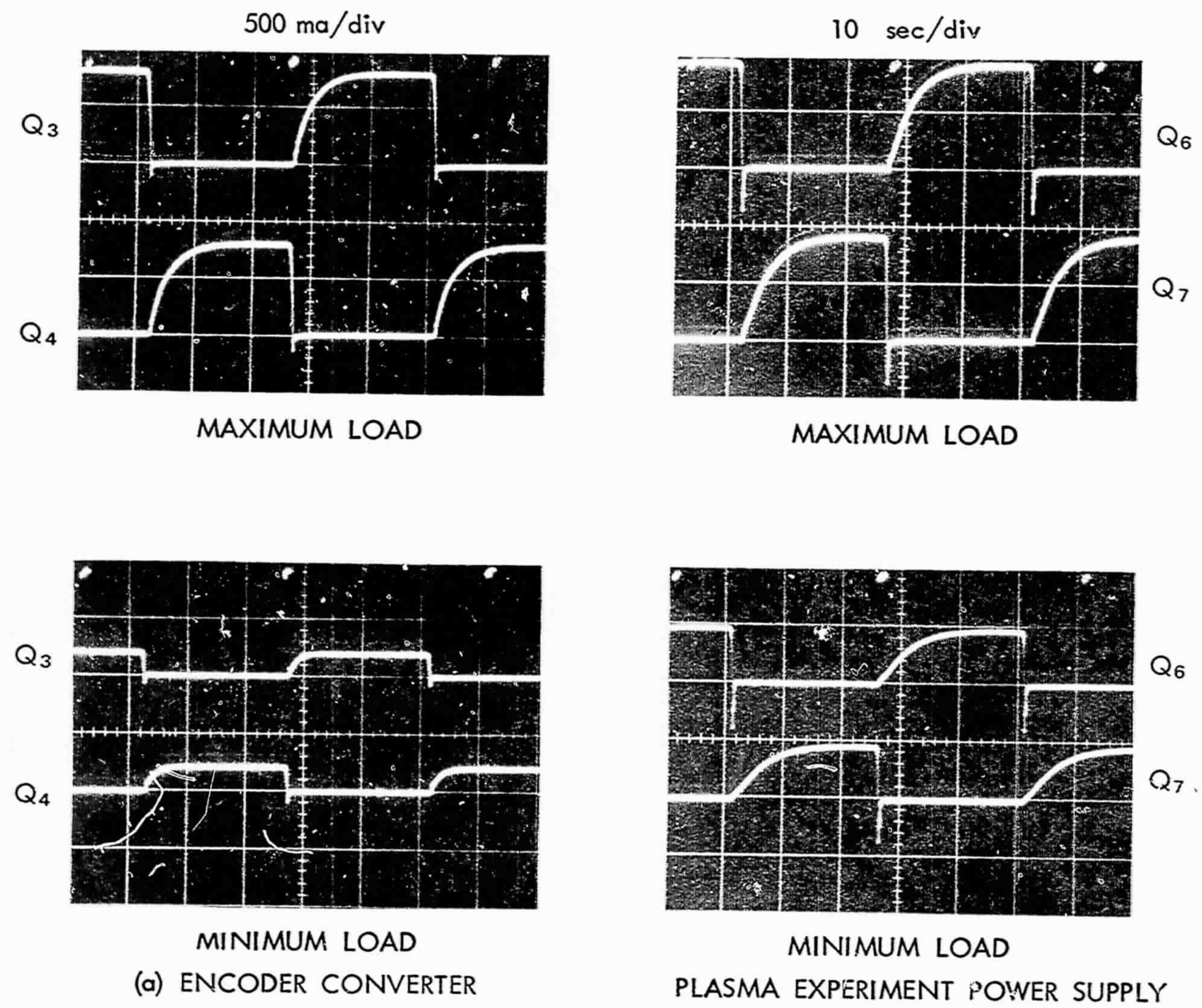


Figure 17. Synchronous Rectifier Collector Currents

The synchronous rectifier has another big advantage over the diode rectifier which is lower power loss. This is evident from Figure 16 which shows, at a load current of 800 ma, a voltage drop of 0.13 volts across the 2N2854 and 0.76 volts across the U-766 diode. The total savings in power at maximum load in both units is approximately one watt. There is still another advantage of the synchronous rectifier and that is the output temperature coefficient, as evidenced by Figure 25 and Figure 27. The temperature coefficient is approximately zero at maximum load and slightly negative at minimum load.

SHORT CIRCUIT PROTECTION

As noted in the initial specifications, the Plasma Experiment power supply was required to turn off in the event of a short on any or all outputs, and come back to normal operation upon the removal of the short(s). Many schemes were considered before settling on the one eventually used. Among the techniques initially considered were:

a. Current sensing and limiting in the input regulator. This was found to be impractical since the input current goes up very little or even down slightly from maximum load when the converter output is shorted. In this condition the oscillator dissipates the entire input power, with the result of overheating and probable failure of the switching transistors.

b. Placing output regulators on all outputs with built in current limiting. This was deemed undesirable since heavy emphasis was placed on maximizing the efficiency and, in addition, a large number of parts would be required.

The technique used is shown in Figure 10. Each output has a current sensing transformer, T3 through T7. The primaries of these transformers are in series with the rectifier diodes or transistors, and the secondaries develop a voltage, proportional to the load current, across resistors R14 through R18. If any of these voltages rises to a preset level, sufficient gate current will be developed to trigger SCR Q8, discharging C16. Q8 then turns off since the current through R21 is insufficient to keep it in conduction. While C16 is charging back to 28 volts Q9 keeps Q10 full on, which in turn holds the input regulator off. As C16 approaches full charge, Q9 and Q10 turn off and the input regulator comes on. Capacitor C1 causes a gradual turn on of the regulator which keeps the inrush current to the rectifier capacitors from triggering the SCR Q8. Capacitor C15 also helps keep this and other sudden transients from triggering the SCR.

Resistors R14 through R18 are adjusted so that the SCR will be triggered if any output current becomes approximately twice its normal maximum value. If the overload or short remains on the output, the circuit keeps pulsing on about once a second just long enough for the fault current to retrigger the SCR, which is on the order of about 10 milliseconds.

Using the SCR in this manner requires some precautions. The device triggers positively as the gate voltage increases to the proper level. However, as the gate voltage gets very close to that necessary to supply sufficient triggering current, the SCR can get slightly leaky. Resistor R21 and R37 are such as to keep this from turning on Q9 and Q10 before full triggering occurs.

A slight modification of the technique could be used if it were not necessary for the power supply to turn on automatically upon removal of the overload fault. R21 could be reduced to about 10,000 ohms and C16 removed completely. In the event of a short, Q8 would trigger on and stay on, holding the power supply off. The unit could be turned back on by commanding off the faulty load and the input voltage. This would turn off the SCR, after which the input voltage could be commanded back on.

The total power consumed by the overload protection circuit at normal maximum load is approximately six milliwatts.

CIRCUIT OPERATION

Figure 18 through Figure 23 show sample operating waveforms. These are fairly typical of all three power supplies. The Encoder Converter and Decoder Converter used LC feedthrough filters on all input and output lines, while, due to space limitations, the Plasma Experiment power supply did not. Figures 21 through 23 readily shows the advantages of using these feedthrough filters, since the Encoder and Decoder Converters are totally free of noise producing high frequency spikes.

Figures 24 through 27 show the performance, under various operating conditions, of the three power supplies.

Figures 28 through 33 show two views of each power supply. Most of the magnetics are seen to be contained in cans. This was for the purpose of helping to meet the AC magnetic field requirement of the IMP-I spacecraft, and will be covered in a separate document. The Encoder Converter utilizes two power transformers as seen in Figures 9 and 30. This helped considerably in maintaining a 5% tolerance on the -2 volt output without using regulation.

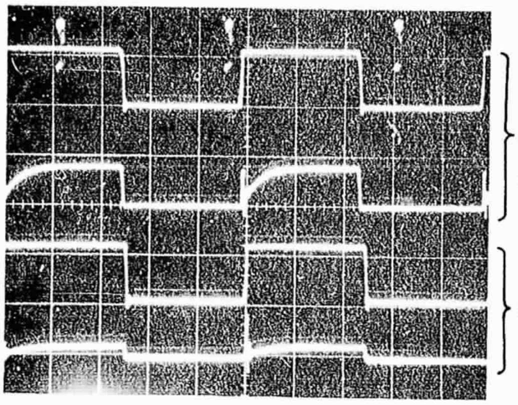


Figure 18. Encoder Converter Collector Voltage and Current for Q1

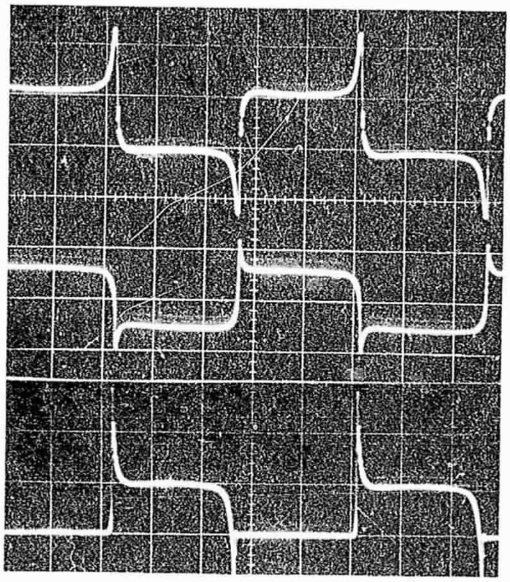


Figure 19. Plasma Experiment Feedback Current (thru R11), Base Driving Voltage and Base Current, Top to Bottom

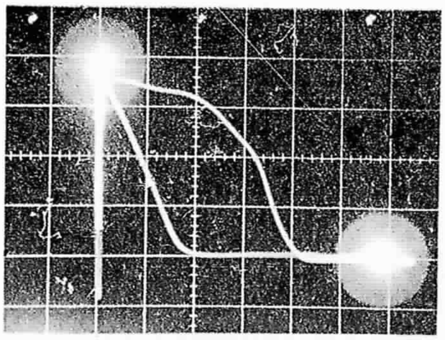


Figure 20. Operating Load line of Q1 in the Encoder Converter at maximum load. Time in dissipative region less than 0.5 sec. Top trace is turn on.

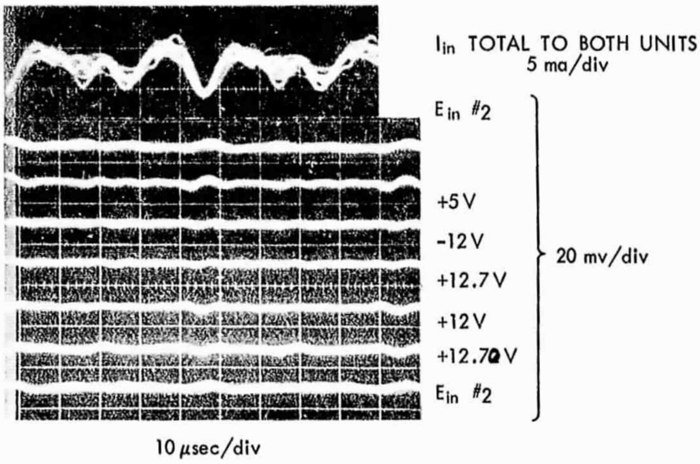


Figure 21. Decoder Converter Input and Output Ripples, Maximum Load

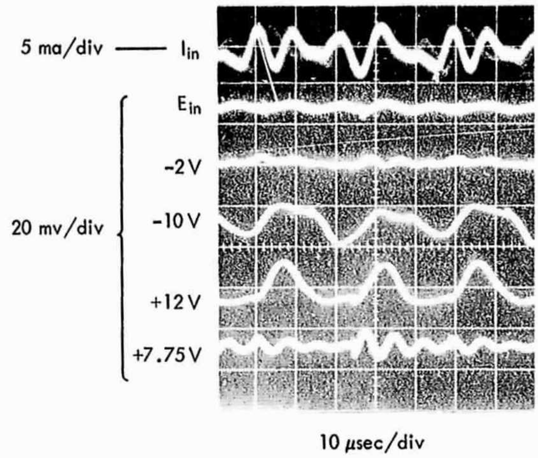


Figure 22. Encoder Converter Input and Output Ripples, Maximum Load

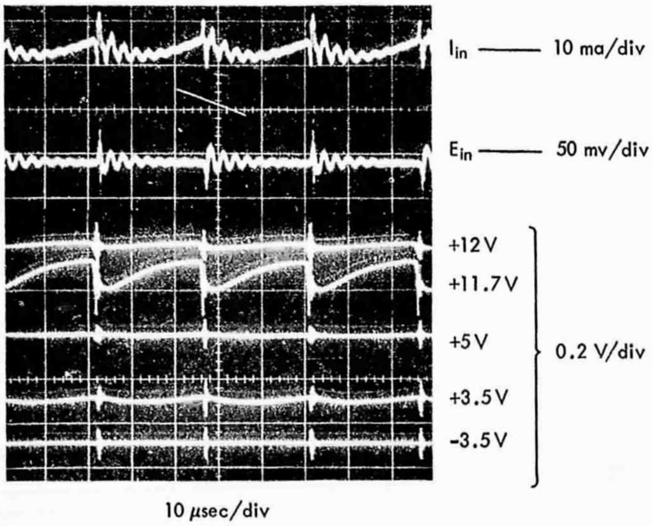


Figure 23. Plasma Experiment Power Supply Input and Output Ripples, Maximum Load

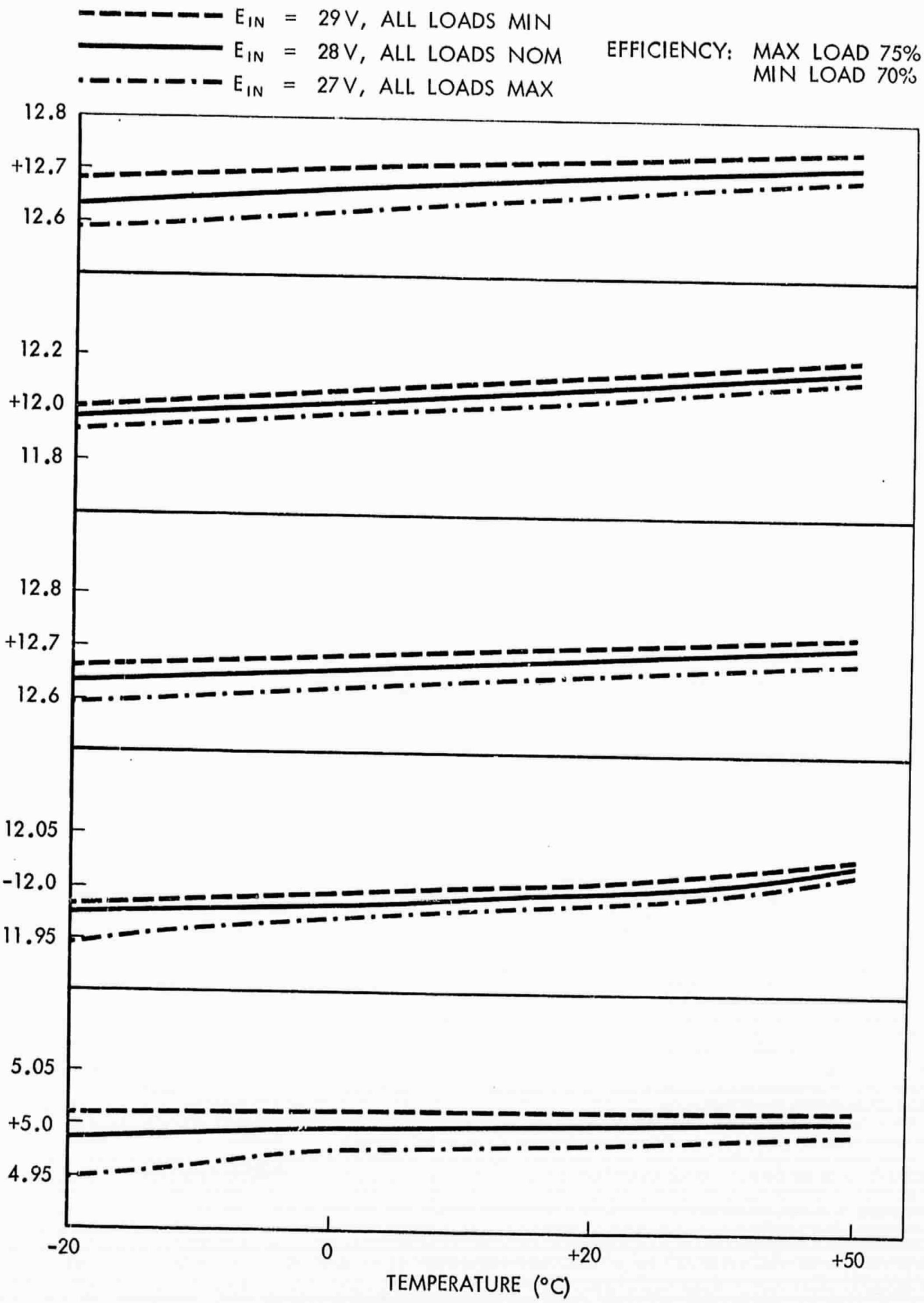


Figure 24. Decoder Converter Output Voltages Under Various Operating Conditions

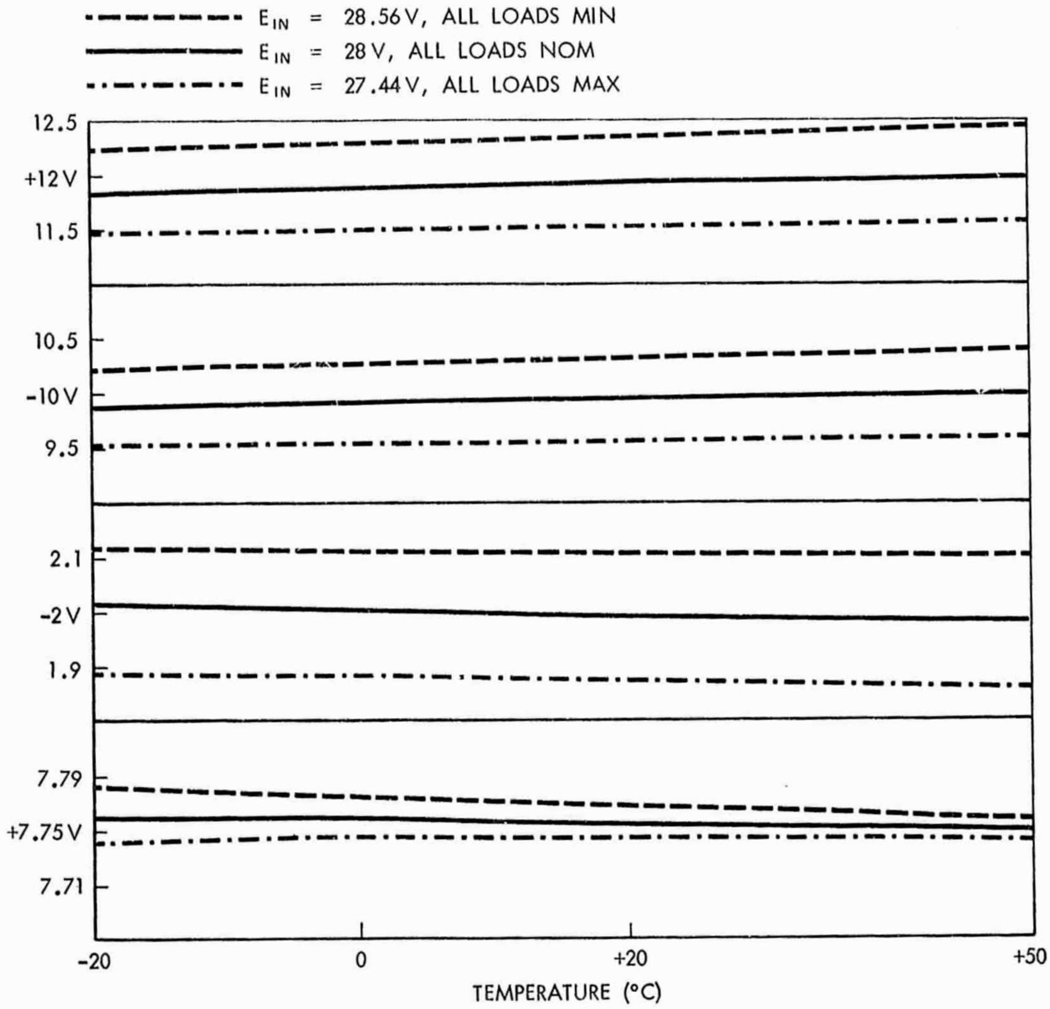


Figure 25. Encoder Converter Output Voltages Under Various Operating Conditions

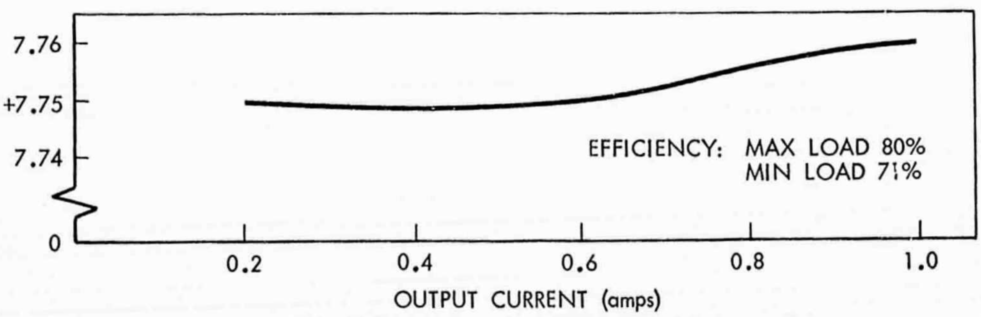


Figure 26. Encoder Converter 7.75V Output as a Function of Load at Room Temperature

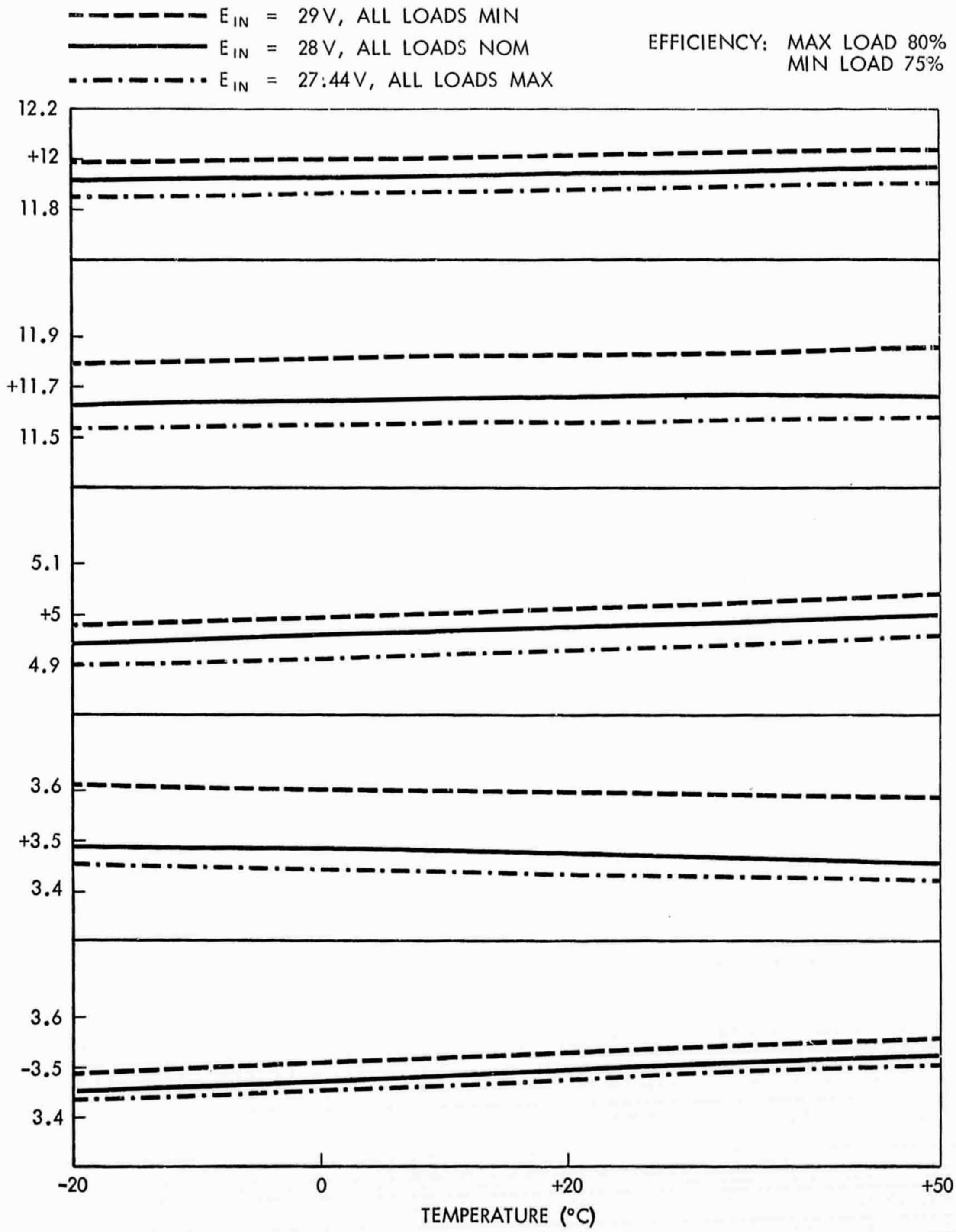


Figure 27. Plasma Experiment Power Supply Output Voltages Under Various Operating Conditions

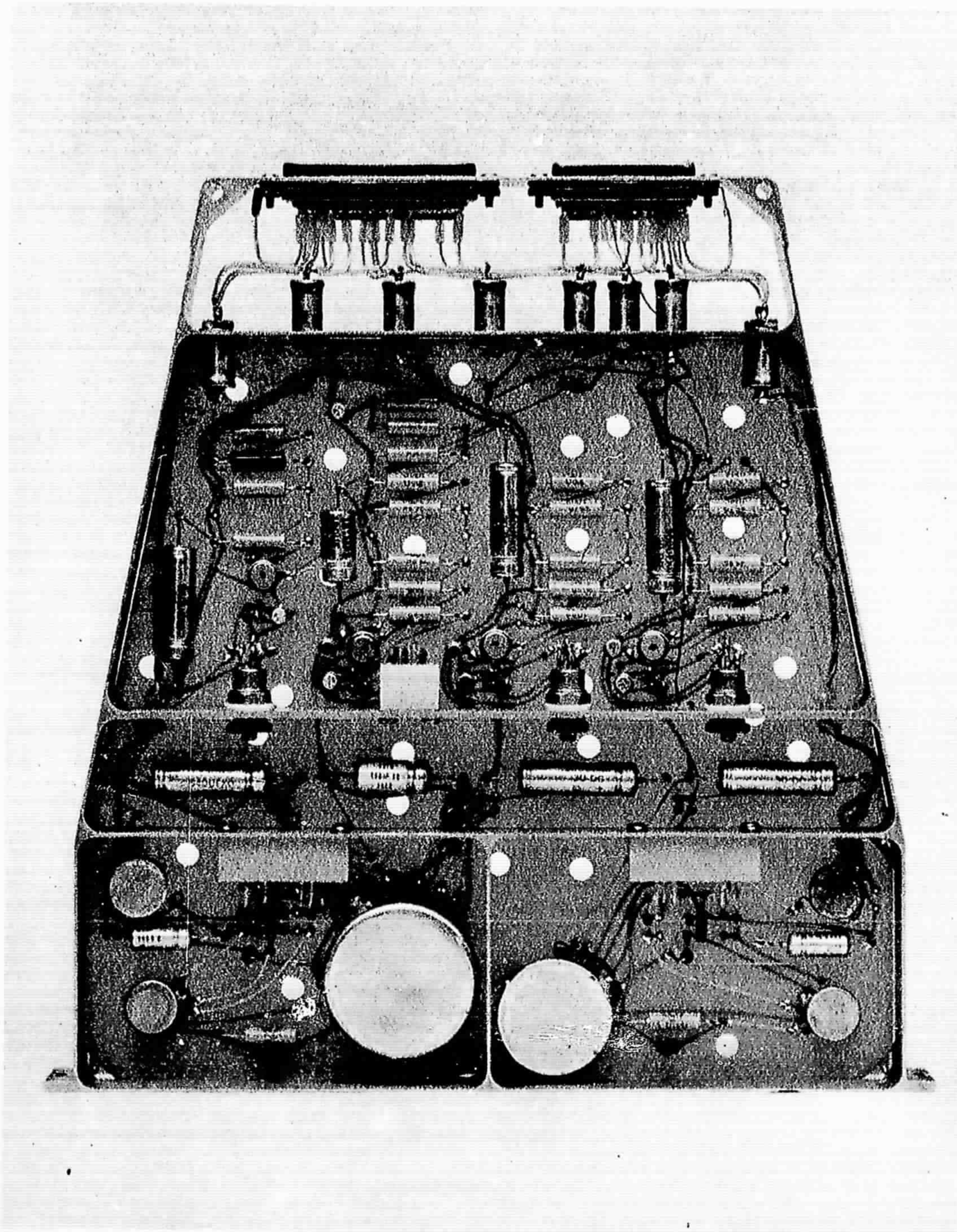


Figure 28. Decoder Converter

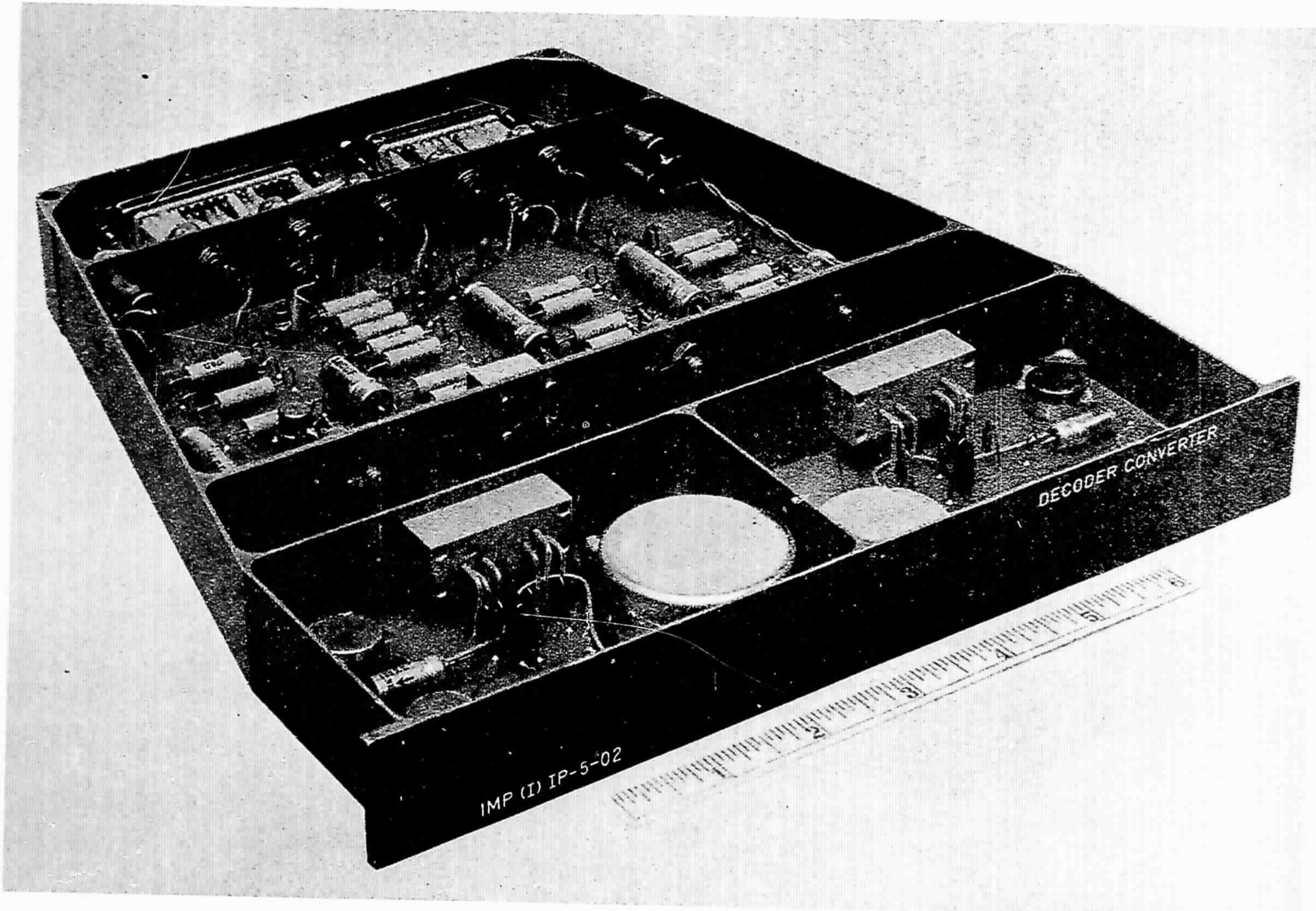


Figure 29. Decoder Converter

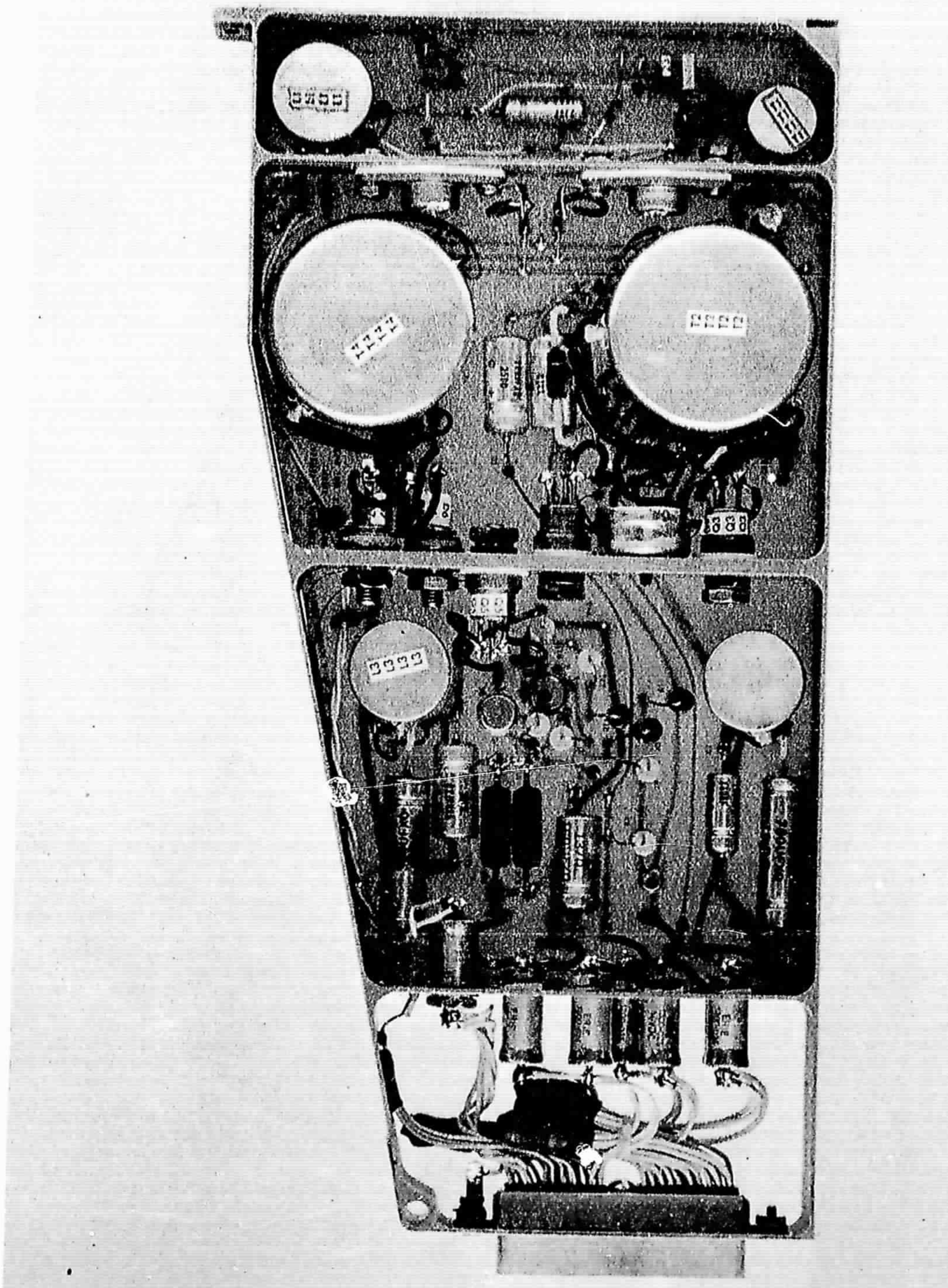


Figure 30. Encoder Converter

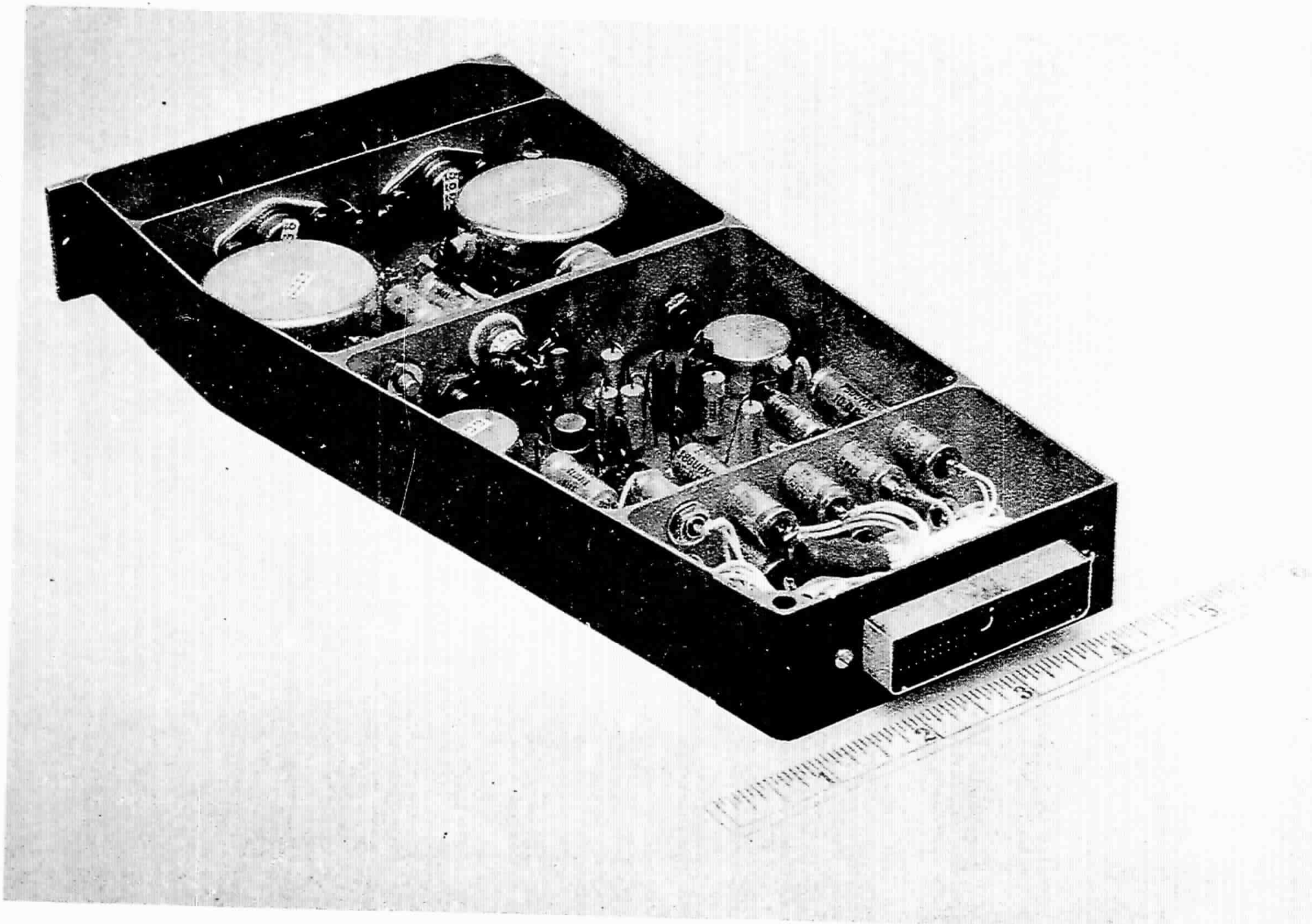


Figure 31. Encoder Converter

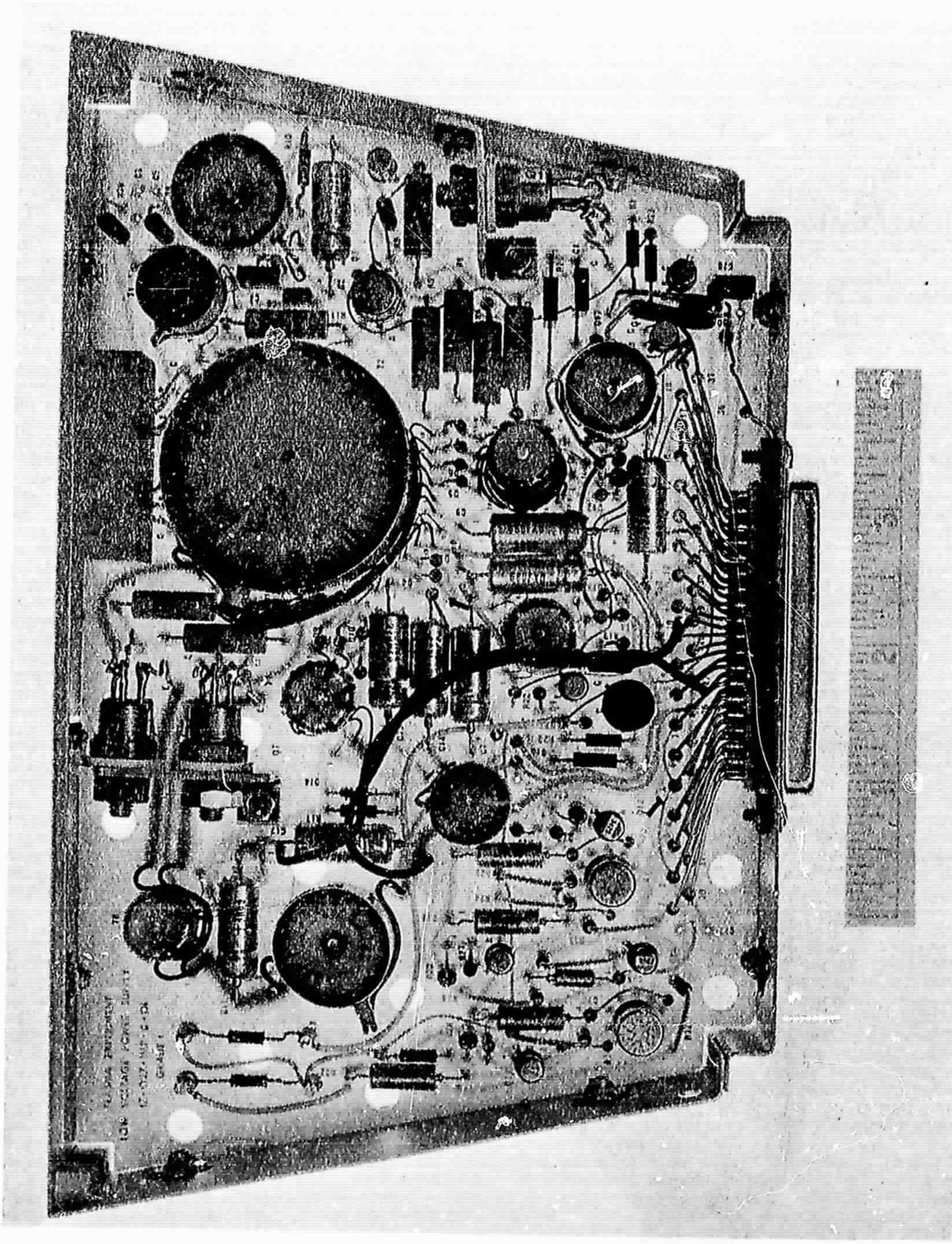


Figure 32. Plasma Experiment Power Supply

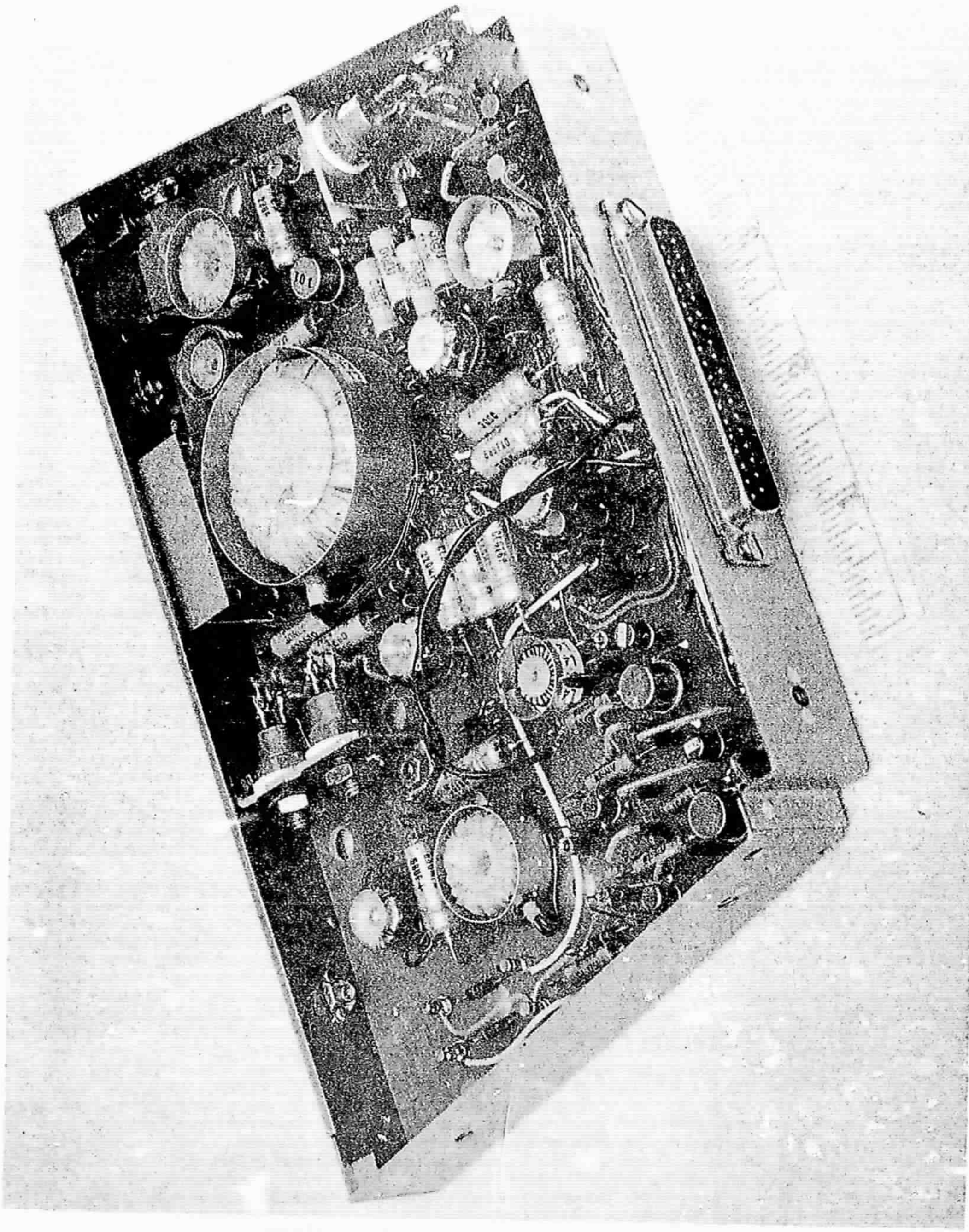


Figure 33. Plasma Experiment Power Supply

APPENDIX A

TRANSFORMER AND INDUCTOR DESIGN INFORMATION

Decoder Converter

T1 and T3	Arnold 12634P250-75 N_{1-2} = 165T AWG 32 N_{3-4} = N_{5-6} = 32T AWG 32
T2	Arnold 6T5515-S1 N_{1-2} = N_{3-4} = 200T AWG28 N_{5-6} = 146T AWG32 N_{7-8} = N_{9-10} = 107T AWG26
T4	Arnold 6T4168-S1 N_{1-2} = N_{3-4} = 200T AWG26 N_{5-6} = 143T AWG32 N_{7-8} = N_{9-10} = 107T AWG25 N_{11-12} = N_{13-14} = 102T AWG32 N_{15-16} = N_{17-18} = 49T AWG26
L1	Magnetics 55050-A2 60T AWG27
L2	Magnetics 55050-A2 75T AWG25

Encoder Converter

T1	Arnold 12634P250-75 N_{1-2} = N_{3-4} = 32T AWG32 N_{5-6} = 165T AWG32
T2	Arnold 6T7699-S1 N_{1-2} = N_{3-4} = 296T AWG27 N_{5-6} = 225T AWG32 N_{7-8} = N_{9-10} = 134T AWG30 N_{11-12} = N_{13-14} = 113T AWG30 N_{15-16} = N_{17-18} = 23T AWG18 N_{19-20} = N_{21-22} = 16T AWG32

APPENDIX A (Continued)

T3	Arnold 15567P1000-37				
	N_{1-2}	= N_{3-4}	= 200T	AWG34	
	N_{5-6}	= N_{7-8}	= 6T	AWG20	
T4	Arnold 6T7699-S1				
	N_{1-2}	= N_{3-4}	= 150T	AWG23	
	N_{5-6}	= N_{7-8}	= 52T	AWG19	
L1-L3	Magnetics 55120-A2				
	L1	80T	AWG22		
	L2	22T	AWG18		
	L3	28T	AWG20		

Plasma Experiment Power Supply

T1	Arnold 12634P250-75				
	N_{1-2}	= N_{3-4}	= 32T	AWG32	
	N_{5-6}	=	168T	AWG32	
T2	Magnetics 52011-1F				
	N_{1-2}	= N_{3-4}	= 200T	AWG24	
	N_{5-6}	=	147T	AWG34	
	N_{7-8}	= N_{9-10}	= 96T	AWG33	
	N_{11-12}	= N_{13-14}	= 94T	AWG26	
	N_{15-16}	= N_{17-18}	= 43T	AWG26	
	N_{19-20}	= N_{21-22}	= 28T	AWG19	
	N_{23-24}	= N_{25-26}	= 10T	AWG30	
	N_{27-28}	= N_{29-30}	= 33T	AWG29	
T3-T7	Arnold 18282P1000-45				
	N_{1-2}	= 500T	AWG36		
T3	N_{3-4}	= N_{5-6}	= 40T	AWG32	
T4	N_{3-4}	= N_{5-6}	= 25T	AWG25	
T5	N_{3-4}	= N_{5-6}	= 3T	AWG24	
T6	N_{3-4}	= N_{5-6}	= 1T	AWG18	
T7	N_{3-4}	= N_{5-6}	= 8T	AWG26	
L1	Magnetics 55117-A2				
	51T	AWG25			
L2	Magnetics 55048-A2				
	30T	AWG24			

APPENDIX A (Continued)

L3	Magnetics 55118-A2 22T AWG18
L4	Magnetics 55037-A2 27T AWG27